

On the origin of brown dwarfs and free-floating planetary mass objects

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ABSTRACT

Briceno et al. report a significantly smaller number of brown dwarfs (BDs) per star in the Taurus-Auriga (TA) pre-main sequence stellar groups than in the central region of the Orion Nebula cluster (ONC). Also, BDs have binary properties that are not compatible with a star-like formation history. It is shown here that these results can be understood if BDs are produced as ejected embryos with a dispersion of ejection velocities of about 2 km/s and if the number of ejected embryos is about one per four stars born in TA and ONC. The Briceno et al. observation is thus compatible with a universal BD production mechanism and a universal IMF, but the required number of BDs per star is much too small to account for the one BD per star deduced to be present in the Galactic field. There are two other mechanisms for producing BDs and free-floating planetary-mass objects (FFLOPs), namely the removal of accretion envelopes from low-mass proto-stars through photo-evaporation through nearby massive stars, and hyperbolic collisions between proto-stars in dense clusters. The third BD flavour, the collisional BDs, can be neglected in the ONC. It is shown that the observed IMF with a flattening near $0.5 M_{\odot}$ can be re-produced via photo-evaporation of proto-stars if they are distributed according to a featureless Salpeter MF above the sub-stellar mass limit, and that the photo-evaporated BDs should have a smaller velocity dispersion than the stars. The number of photo-evaporated BDs per star should increase with cluster mass, peaking in globular clusters that would have contained many stars as massive as $150 M_{\odot}$. The required number of embryo-ejected BDs in TA and the ONC can be as low as 6 ejected BDs per 100 stars if the central ONC contains 0.23 photo-evaporated BDs per star. Alternatively, if the assumption is discarded that embryo ejection must operate equally in all environments, then it can be argued that TA produced about one ejected BD per star leading to consistency with the Galactic-field observations. The dispersion of ejection velocities would be about 3 km/s. In the central ONC the number of ejected BDs per star would then be at most 0.37, or less if photo-evaporated BDs contribute. This non-universal scenario would thus imply that the Galactic-field BD population may mostly stem from TA-like star formation or modest clusters, the ONC not being able to contribute more than about 0.25 ± 0.04 BDs per star.

Key words: stars: formation – stars: low-mass, brown dwarfs – binaries: general – open clusters and associations: general – Galaxy: stellar content

1 INTRODUCTION

The failure until a few years ago to find sub-stellar-mass objects ($m < 0.08 M_{\odot}$) posed a long-standing unsolved problem because theoretical considerations (e.g. Boss 1986, 2001; Kumar 2001) suggested that opacity-limited fragmentation may proceed down to $0.001 - 0.01 M_{\odot}$. According to this argument, a dense molecular cloud region contracts with constant temperature and rising density so that the Jeans mass becomes smaller allowing smaller fragments to form as time progresses. The collapse

leads to an increasing opacity which ultimately increases sufficiently to prohibit radiative cooling of the core. The core heats up and the Jeans mass increases, thus leading to the above minimum fragmentation mass. On the other hand, arguments had been put forward (e.g. Adams & Fatuzzo 1996) that the hydrostatic core, which forms within a fragment once opacity stops significant radiative cooling, would continue to accrete from an envelope, which always exceeds the hydrostatic core mass by large factors, until feedback reverses the infall. Feedback energy comes from collimated outflows and the luminosity of the protostar due to accretion luminosity, deuterium burning and finally hydrogen burning. The typical conditions in dense molecular cloud regions are such that the formation of sub-stellar mass objects, that require very feeble mass-accretion rates, is unlikely. This fitted rather well with the non-detection of these objects, and one could begin feeling somewhat comfortable with this null result.

However, since a few years ago sub-stellar-mass objects are being discovered in increasing numbers (e.g. Basri 2000). Sub-stellar-mass objects can be split into two broad categories, brown dwarfs (BDs, $0.01 \lesssim m/M_{\odot} \lesssim 0.08$) and low-mass BDs orbiting a star or a BD, or free-floating planetary-mass objects (FFLOPs, $m \lesssim 0.01 M_{\odot} \approx 10 M_{\mathrm{J}}$, $M_{\mathrm{J}} = \mathrm{Jupiter~mass}$). Differentiating between massive planets and low-mass BDs orbiting a star is difficult observationally. Theoretically, they can be distinguished according to whether their formation involved the initial condensation of solids in a circum-stellar disk (yielding planets) or the collapse of a cloud or disk fragment (e.g. Kumar 2002). The internal structure and constitution of BDs and FFLOPs is over-viewed by Chabrier & Baraffe (2000).

BDs and FFLOPs have been found in a number of very young clusters where they are most easily detected given that they fade with time (Lucas & Roche 2000; Zapatero Osorio et al. 2000, Muench, Lada & Lada 2000; Bouvier et al. 2002; Moraux et al. 2003; Muench et al. 2002, 2003). Measurements of the mass functions (MFs) in five clusters indicate that their distribution can be described with a power-law function, $\xi(m) \propto m^{-\alpha}$, where $\xi(m) dm$ is the number of stars (or BDs and FFLOPs) in the mass interval $m, m + dm$, and $\alpha = +0.5 \pm 0.1$ between about 0.03 and $0.3 M_{\odot}$ (Bouvier et al. 2002). The initial MF (IMF) of stars can be represented by the standard form $\alpha = +1.3 \pm 0.5$, $0.08 \leq m/M_{\odot} \leq 0.5$ and $\alpha = +2.3 \pm 0.3$, $0.5 < m/M_{\odot}$ (Kroupa 2002). Such structure in the IMF contains information on the processes active in the conversion of interstellar gas to stars, BDs and FFLOPs. And in particular, variations of structure in the IMF between different star-formating regions, if found, would place important constraints on our understanding of how their formation proceeds.

The discovery by Briceno et al. (2002) that star formation in Taurus–Auriga (TA) seems to be producing significantly fewer BDs, with masses in the range $0.02 – 0.08 M_{\odot}$, per low-mass stellar system than the star-formation event that formed the much denser Orion Nebula cluster (ONC) may thus pose a real break-through. According to this result, the IMF for BDs (and probably FFLOPs) may be dependent on environment, while the stellar IMF seems to be invariant and consistent with the standard form (fig. 11 in Briceno et al. 2002; Kroupa et al. 2003, hereinafter KBDM).

The reported variation in the BD mass regime may be a result of star-formation proceeding under different conditions. For example, the Jeans mass was much smaller in the ONC precursor than in TA which is at least qualitatively consistent with the smaller number of BDs per star seen in TA (Briceno et al. 2002). Indeed, a number of authors have found evidence that BDs form just like stars. The measured longevity of circum-BD disks is generally taken to imply disk masses that are not consistent with having been truncated through ejections (Liu et al. 2002), while White & Basri (2002) discard the ejection hypothesis because they also find young BDs to possess accretion disks and the BDs in TA to have indistinguishable kinematics from the stars. Based on the measured properties of the dust disk around the BD GY11 in ρ Oph, Testi et al. (2002) conclude that BDs form like stars by core contraction, gravitational collapse and accretion, while most BD candidates in the central region of the ONC and in ρ Oph also appear to sport disks thus likewise indicating a similar origin as stars (Muench et al. 2001; Natta et al. 2002).

If BDs have the same general formation history as stars then they will have formed from very-low mass cloud cores and ought to have binary properties that are a natural extension of those of late-type stars (Delgado-Donate, Clarke & Bate 2003). If this were to be the case then a possible reason as to why the number of BDs is smaller in TA than in ONC may be because the ONC is dynamically more evolved. In TA BDs may remain locked-up in binary systems. Indeed, KBDM show that the observed different number of BDs per stellar system in TA and the ONC is obtained nearly exactly if it is assumed that BDs and stars form according to the same rules, i.e. that the initial pairing properties of BDs and stars do not differ. These pairing properties are described by the *standard model of star formation* extended into the sub-stellar mass range. According to this model stars and BDs form in binaries with companion masses picked randomly from the IMF, i.e. that there is no sudden change in pairing properties below the hydrogen-burning mass limit. Encounters in dense clusters (such as the ONC) preferentially destroy binaries with weaker binding energy leading to a larger number of free-floating BDs than in environments that are dynamically unevolved (such as TA). This process has also been studied by Adams et al. (2002) for the Pleiades and Hyades clusters.

While the standard model with BDs arrives at the correct relative number of BDs per stellar system, it also makes predictions on the binary fraction of stellar and BD systems and their distribution of semi-major axes. Comparison of these predictions with the available binary statistics demonstrates that the standard model with BDs cannot be the solution to the differences seen by Briceno et al. (2002). Changing the IMF (as suggested by Briceno et al.) to model its possible dependence

on the Jeans mass does not lead to a model which is consistent with both the number of BDs per stellar system and with the binary statistics in the TA star-formation rate.

The conclusion is therefore that in TA the BDs follow different pairing rules, i.e. that they cannot have formed with the same binary properties as stars. The standard model with BDs fails. Because the standard model (without BDs) leads to excellent agreement to the observational data in TA, the ONC and Pleiades, as well as the Galactic-field stellar population, KBDM suggest *that BDs need to be added as a separate, primarily single-object population*. This is supported by the conclusions made by Close et al. (2003) based on their survey of the binary properties of very-low mass stars and BDs in the solar neighbourhood. Thus, BDs do not appear to have the same general formation history as stars.

There exist four broad formation scenarios for BDs and FFLOPs: (i) in contracting cloud fragments like stars with accretion from an envelope until feedback from the hydrostatic core halts accretion (the *star-like model*), (ii) through ejection from dynamically unstable multipleproto-stellar systems and the consequent loss of the accretion envelope (the *embryo-ejection model*), (iii) removal of the accretion envelope due to photo-evaporation through a nearby massive star (the *photo-evaporation model*), or (iv) separation of embryos from their accretion envelopes through hyperbolic encounters in dense embedded clusters (the *collision model*). Note that according to scenarios (ii)–(iv) the star-like formation process (i) is terminated through the loss of the accretion envelope. Another scenario for the formation of FFLOPs as being planets that were lost from their parent stars through stellar-dynamical encounters cannot operate to produce a significant number of the observed FFLOPs in young clusters, because the cross-section of typical planetary systems is too small and the potential wells of the clusters are too shallow to retain the so-produced FFLOPs (Smith & Bonnell 2001).

Only scenarios (i) and (ii) can be valid in the TA star-formation rate because there are no hot ionising stars there and the densities are too low, but (i) is unlikely to be a major BD production channel given the results of KBDM: There are virtually no BD binaries in TA, but a high BD binary fraction would be expected. In the ONC all four scenarios may have played a role (binary statistics do not yet exist for the BDs and FFLOPs in the ONC). However, it would appear as very unlikely that scenario (i) may have acted in the ONC but not in the much more tranquil TA star-formation region which is more likely to allow the subtle conditions leading to the very low accretion rates needed to assemble a BD system. Scenario (i) can therefore probably be excluded as a significant source of sub-stellar mass objects. This conclusion is consistent with the finding by Close et al. (2003), Gizis et al. (2003), Bouy et al. (2003) and Martín et al. (2003) that very-low-mass solar-neighbourhood and Pleiades stars and BDs appear to have binary properties that are inconsistent with an extrapolation of those of M–G dwarfs, or with a scaling to T Tauri stars.

In what follows the embryo-ejection scenario and its implications are considered (§ 2), followed by an investigation of the implications of the photo-evaporation model (§ 3). Section 4 discusses the collision model. A combination of the three models is studied in § 5, and § 6 finds that the birth-rate per star of BDs may differ significantly in different star-forming environments if the Galactic-field BD density has been correctly estimated. The conclusions are presented in § 7.

2 THE EMBRYO-EJECTION MODEL

If massive proto-stellar disks with radii ≈ 100 AU fragment rapidly to form many massive planets then this system relaxes within 100 orbits ($\approx 10^5$ yr) by ejecting most of the planetary siblings that become FFLOPs into the cluster leaving one to a few bound to the parent star (Papaloizou & Terquem 2001). The remaining star-planet system will typically have the most massive planet on an eccentric, short-period orbit. The dramatic rise of the BD MF below $0.03 M_\odot$ found by Muench et al. (2002, 2003) in the central ONC and in IC 348 may pose tentative support for this scenario.

According to the recently emphasised embryo-ejection hypothesis (Reipurth & Clarke 2001), BDs (and some FFLOPs) are unfinished stars that were ejected from their natal embedded system (Reipurth 2000; Bate, Bonnell & Bromm 2002; Delgado-Donate, Clarke & Bate 2003). The fragmentation of a cloud core (or kernel according to Myers 1998) with a mass of $M = 1 M_\odot$ and a radius of $R = 1000$ AU typically forms a few accreting hydrostatic cores. A non-hierarchical system of a few bodies is dynamically unstable and decays within a few system dynamical times,

$$t_{\text{dyn}} \approx 0.5 M_{[M_\odot]}^{-1/2} R_{[\text{AU}]}^{3/2} = 1.6 \times 10^4 \text{ yr}, \quad (1)$$

by typically ejecting the least-massive member (Sterzik & Durisen 1998). Ejections continue on the new shorter dynamical time-scale of the shrunk (hardened) system leaving one binary or a strongly hierarchical and thus long-lived multiple system.

The one high-resolution computation of a fragmenting cloud by Bate, Bonnell & Bromm (2002, 2003) confirms that the ejection of unfinished stars occurs rather often. This computation models the fragmentation of a small proto-cluster, and is thus applicable to star formation in TA rather than in the ONC. The computation suggests that about the same number of BDs are formed as low-mass stars. This large production rate of about one BD per star may decrease in a computation that is allowed to proceed for a longer time, in which case some of the hydrostatic cores may accrete sufficient mass to become stars. Furthermore, the presently feasible hydrodynamical collapse computations lack feedback through radiation, winds and outflows, which in reality begin to heat a collapsing cloud as soon as the first accreting hydrostatic core forms, thus limiting

the number density of accreting hydrostatic cores, and therefore the ejection rate of unfinished stars may be reduced. On the other hand, radiation and outflows may trigger new formation or destroy envelopes. It will be a very serious challenge to include these computationally extremely costly effects in future collapse calculations. *The real production rate of BDs as ejected embryos may therefore differ from what the presently available hydrodynamical computations suggest.*

The predictions of the embryo-ejection model are as follows: (i) The typical ejection velocities are $v_{\text{ej}} \approx 15 R_{\text{C},[\text{AU}]}^{-1/2} \lesssim 2 \text{ km/s}$ for closest-approach distances $R_{\text{C}} \gtrsim 56 \text{ AU}$, but a high-velocity tail exists (Sterzik & Durisen 1995; Reipurth & Clarke 2001; Sterzik & Durisen 2003; Delgado-Donate et al. 2003). (ii) The so-formed BDs have a very small binary fraction, although BD-BD binaries with semi-major axis $a \lesssim 0.5 \times R_{\text{C}}$ can survive the ejection process, and (iii) the ejected BDs can also retain accretion disks with radii $< 0.5 \times R_{\text{C}}$. The hydrodynamical collapse calculations reported by Bate et al. (2002; 2003) show that most (14) of their 18 BDs are ejected and have disks with radii $\lesssim 10 \text{ AU}$. The low binary proportion is qualitatively consistent with available surveys for BDs, and while a large fraction of young BDs have infrared excesses indicative of disks (Muench et al. 2001; Liu, Najita & Tokunaga 2002; Natta et al. 2002), their sizes are not yet known.

If embryo ejection is the dominant source of most BDs in TA and in the ONC, then we would like to know if the different gravitational potentials of the star-forming regions (TA vs ONC) can lead to the observed difference between the fraction of BDs that are retained in the stellar group or star cluster (Bouvier et al. 2001). This is estimated here by making the ansatz that embryo ejection occurs exactly alike in the vastly different TA and ONC environments by requiring the number of BDs per star to be the same and that the ejected embryos have, as a population, an isotropic Schwarzschild velocity distribution function with a one-dimensional velocity dispersion $\sigma_{1\text{D}}$,

$$h(v) = \frac{1}{(2\pi\sigma_{1\text{D}}^2)^{3/2}} e^{-\frac{1}{2}\left(\frac{v}{\sigma_{1\text{D}}}\right)^2}, \quad (2)$$

where v is the 3D speed. The ansatz is basically the assumption that embryo ejection occurs from fragmented cloud kernels that have the same statistical properties on scales below a few hundred AU in TA and the proto-ONC. Both the TA groups and the ONC are about 1 Myr old so that the vast majority of dynamical decays will have occurred to completion and therefore very few if any further BDs are expected to be produced. The velocity dispersion is made up (i) of contributions from kernel–kernel motions, i.e. the velocity dispersion of the embedded cluster with mass $M_{\text{ecl+g}}$ (stars plus gas) which is approximately in global virial equilibrium (Kroupa & Boily 2002), and (ii) the ejected BDs,

$$\sigma_{1\text{D}}^2 = \sigma_{\text{cl},1\text{D}}^2 + \sigma_{\text{ej},1\text{D}}^2, \quad (3)$$

where $\sigma_{\text{cl},1\text{D}}^2 = G M_{\text{ecl+g}} / 2 R_{0.5}$, $G = 0.0045 \text{ pc}^3 / (M_{\odot} \text{ Myr}^2)$ is the gravitational constant and $R_{0.5}$ is the half-mass radius. According to the above ansatz $\sigma_{\text{ej},1\text{D}}$ is to be equal in both environments.

A star-formation event produces a total number of BD systems, $N_{\text{BD,tot}}$. According to the results of KBDM we assume these to have the same binary properties independent of environment and the number of BD companions to stars to be negligible. Most BDs are single, with only about 15 per cent or fewer being binaries with semi-major axes $< 15 \text{ AU}$ (Close et al. 2003; Gizis et al. 2003; Bouy et al. 2003; Martín et al. 2003). In what follows we do not distinguish between BD binaries and single BDs, although we note that on average binary BDs should have lower ejection speeds than single BDs by virtue of their higher system masses and necessary lower ejection speeds to guarantee binary survival. Of the total number of BDs, $N_{\text{BD,obs}}$ are observed. These can be split into two populations: The bound BDs with velocities smaller than the escape speed, v_{esc} , from the stellar group or cluster, and the unbound BDs which remain within the survey region. The number of unbound but observable BDs can be estimated by calculating the number of BDs with velocities in the interval v_{esc} to v_{in} , where v_{in} is given roughly by $v_{\text{in}} = r_{\text{in}}/\tau$. Here r_{in} is the radius of the survey volume ($r_{\text{in,TA}} = 2.3 \text{ pc}$ for the TA groups, while $r_{\text{in,ONC}} = 0.5 \text{ pc}$ for the central ONC), and the age of both the TA and ONC is about $\tau = 1 \text{ Myr}$. Thus,

$$N_{\text{BD,obs}} = N_{\text{BD,tot}} \left(\int_0^{v_{\text{esc}}} h(v) 4\pi v^2 dv + \int_{v_{\text{esc}}}^{v_{\text{in}}} h(v) 4\pi v^2 dv \right), \quad (4)$$

$$\equiv N_{\text{BD,tot}} (\mathcal{B} + \mathcal{U}) \quad (5)$$

where $N_{\text{BD,tot}} h(v) 4\pi v^2 dv$ is the number of BDs with speeds in the interval v to $v + dv$. The “retention integral” $\mathcal{B} = \mathcal{B}(\sigma_{\text{ej},1\text{D}}, M_{\text{ecl+g}})$ ($= \mathcal{B}_{\text{TA}}$ for the TA groups or \mathcal{B}_{ONC} for the ONC), and similarly the “unbound but observable integral” $\mathcal{U} = \mathcal{U}(\sigma_{\text{ej},1\text{D}}, M_{\text{ecl+g}})$ which is zero if $v_{\text{esc}} \geq v_{\text{in}}$.

The observational datum is the number of BDs per stellar system in the group or cluster,

$$\mathcal{R}_{\text{obs}} \equiv \frac{N_{\text{BD,obs}}}{N_{\text{st,obs}}}. \quad (6)$$

According to our ansatz each star-formation event produces the same number of BDs per star,

$$\mathcal{R} \equiv \frac{N_{\text{BD,tot}}}{N_{\text{st,tot}}} = \text{constant}, \quad (7)$$

the BDs and stars having masses in some interval as defined by the observational survey (eq. 14 below). The number of

observed stars is the number of stellar systems, $N_{\text{st,obs}} \equiv N_{\text{st,sys}} = N_{\text{st,bin}} + N_{\text{st,sing}}$, where the total number of stars is $N_{\text{st,tot}} = 2N_{\text{st,bin}} + N_{\text{st,sing}} = (1+f)N_{\text{st,sys}}$. The binary fraction in TA is $f_{\text{TA}} = 1$ while in the ONC it is $f_{\text{ONC}} = 0.5$ (approximately). Thus,

$$\begin{aligned} \mathcal{R}_{\text{obs}} &= \frac{N_{\text{BD,tot}}}{N_{\text{st,sys}}} (\mathcal{B} + \mathcal{U}), \\ &= (1+f) \mathcal{R} (\mathcal{B} + \mathcal{U}). \end{aligned} \quad (8)$$

With $\mathcal{R}_{\text{obs,TA}} = 0.17 \pm 0.06$ for TA and $\mathcal{R}_{\text{obs,ONC}} = 0.38 \pm 0.06$ for the ONC (KBDM, from the data provided by Briceno et al. 2002) the ratio $\mathcal{R}_{\text{obs,TA}} (1+f_{\text{TA}})^{-1}/\mathcal{R}_{\text{obs,ONC}} (1+f_{\text{ONC}})^{-1} \equiv \Lambda_{\text{obs}} = 0.34 \pm 0.05$, where

$$\Lambda(\sigma_{\text{ej,1D}}) \equiv \frac{\mathcal{R} (\mathcal{B}_{\text{TA}} + \mathcal{U}_{\text{TA}})}{\mathcal{R} (\mathcal{B}_{\text{ONC}} + \mathcal{U}_{\text{ONC}})}. \quad (9)$$

The escape speed from the centre of a Plummer sphere, which approximates the structure of the embedded groups and cluster reasonably well for the present purpose, is

$$v_{\text{esc}} = 1.62 \left(\frac{G M_{\text{ecl+g}}}{R_{0.5}} \right)^{\frac{1}{2}}. \quad (10)$$

Assuming a star-formation efficiency of 33 per cent, the mass (stars plus gas) of the typical embedded TA group is approximately $M_{\text{ecl+g,TA}} = 50 M_{\odot}$ (Kroupa & Bouvier 2003) while the embedded cluster mass of the ONC precursor was about $M_{\text{ecl+g,ONC}} = 9000 M_{\odot}$ (Kroupa, Aarseth & Hurley 2001, hereinafter KAH). The half-mass radii of the embedded groups and cluster are approximately $R_{0.5,\text{TA}} = 0.3$ pc and $R_{0.5,\text{ONC}} = 0.4$ pc, giving $v_{\text{esc,TA}} = 1.4$ and $v_{\text{esc,ONC}} = 16.3$ km/s, respectively. The embedded ONC model used here remains embedded for 0.6 Myr. Then the gas is removed on a thermal time-scale, and the cluster evolves to the observed ONC at an age of about 1 Myr and to the observed Pleiades at an age of 100 Myr (KAH). Once the gas is removed the ONC expands, but the BDs retained during the embedded phase with $v < v_{\text{esc}}$ will behave like the stars so that R_{obs} is conserved approximately during the expansion. This will hold true if most of the BDs are ejected early such that the bound BD population has time to relax with the stars, and provided the velocity dispersion of ejected BDs is smaller than the velocity dispersion of stars in the virialised but embedded cluster, $\sigma_{\text{ej,1D}} < \sigma_{\text{cl,1D}} \approx 5$ km/s (KAH), so that the velocity distribution function of BDs and stars will not differ much. The decay of the small- N groups occurs on a time-scale of a few $\times 10^4$ yr $\ll 1$ Myr so that the production of most BDs occurs well before the end of the embedded phase, and we will see that $\sigma_{\text{ej,1D}} < \sigma_{\text{cl,1D}}$ is indeed the case. The TA groups do not evolve significantly during their first Myr (Kroupa & Bouvier 2003).

The aim is now to seek the velocity dispersion $\sigma_{\text{ej,1D}}$ which minimises $|\delta|$, where

$$\delta \equiv \Lambda_{\text{obs}} - \Lambda(\sigma_{\text{ej,1D}}). \quad (11)$$

To this end, the retention and unbound integrals in eq. 5 are solved numerically.

The results are displayed in Fig. 1. More than 80 per cent of all BDs are lost from the typical TA group if $\sigma_{\text{ej,1D}} \gtrsim 1.5$ km/s, while the embedded pre-ONC retains most of its BDs for $\sigma_{\text{ej,1D}} \lesssim 6$ km/s by virtue of its much deeper potential well. The truly interesting result, however, is that there exists one ejection velocity, $\sigma_{\text{ej,1D}} = 2.0^{+0.3}_{-0.5}$ km/s (three-sigma interval: $\delta \in (-0.15, 0.15)$), which simultaneously leads to the observed number of BDs per star in the TA groups and the ONC. Near this velocity there are about two times more unbound BDs in the survey areas of Briceno et al. (2002) than BDs bound to the groups, $\mathcal{U}_{\text{TA}} \approx 2 \times \mathcal{B}_{\text{TA}}$, while the central region of the ONC only contains BDs bound to the cluster, $\mathcal{U}_{\text{ONC}} = 0.0$, $\mathcal{B}_{\text{ONC}} = 1.0$. Changing the mass of the pre-ONC object to $M_{\text{ecl+g,ONC}} = 4500 M_{\odot}$ changes the escape speed to $v_{\text{esc,ONC}} = 11.5$ km/s but has otherwise a negligible effect on the result (e.g. $\delta = 0.288$ instead of 0.292 for $\sigma_{\text{ej,1D}} = 4.0$ km/s, the difference is not evident in Fig. 1).

The number of BDs produced per formed (\mathcal{R}) star can now be estimated. From eq. 8 we obtain

$$\begin{aligned} 0.17 \pm 0.06 &= 2 \mathcal{R}_{\text{TA}} (0.10 + 0.20) \implies \mathcal{R}_{\text{TA}} = 0.28 \pm 0.10, \\ 0.38 \pm 0.06 &= 1.5 \mathcal{R}_{\text{ONC}} (1.0 + 0.0) \implies \mathcal{R}_{\text{ONC}} = 0.25 \pm 0.04, \end{aligned} \quad (12)$$

so that $\mathcal{R}_{\text{TA}} = \mathcal{R}_{\text{ONC}} = \mathcal{R} = 0.21 - 0.29$. This means that the formation of three–five stars leads, on average, to the formation of one BD. The mental image corresponding to this estimate is that *a cloud kernel fragments into a number of hydrostatic cores, which on average leads to the formation of two binary stellar systems that are weakly bound to each other, and one ejected unfinished embryo*.

Returning to eq. 5 we note that by adopting $r_{\text{in}} = 2.3$ pc instead of 1.15 pc for the radius of the 2.3 pc \times 2.3 pc TA survey area the contribution of unbound but visible BDs (\mathcal{U}_{TA}) is overestimated. This overestimate is not serious however, because the model constructed here assumes that the BDs are ejected at $t = 0$ which in reality will not be the case. Some of the BDs ejected during late times will remain within the TA survey areas even if the ejection velocity is larger than the formal v_{in} . As an extreme example of the relative insensitivity of the results, $r_{\text{in}} = 0$ (no unbound BDs whatsoever in the survey area, $\mathcal{U}_{\text{TA}} = 0$) leads to similar results: $\sigma_{\text{ej,1D}} \approx 1.3$ km/s and $\mathcal{R}_{\text{TA}} \approx \mathcal{R}_{\text{ONC}} \approx 0.25$.

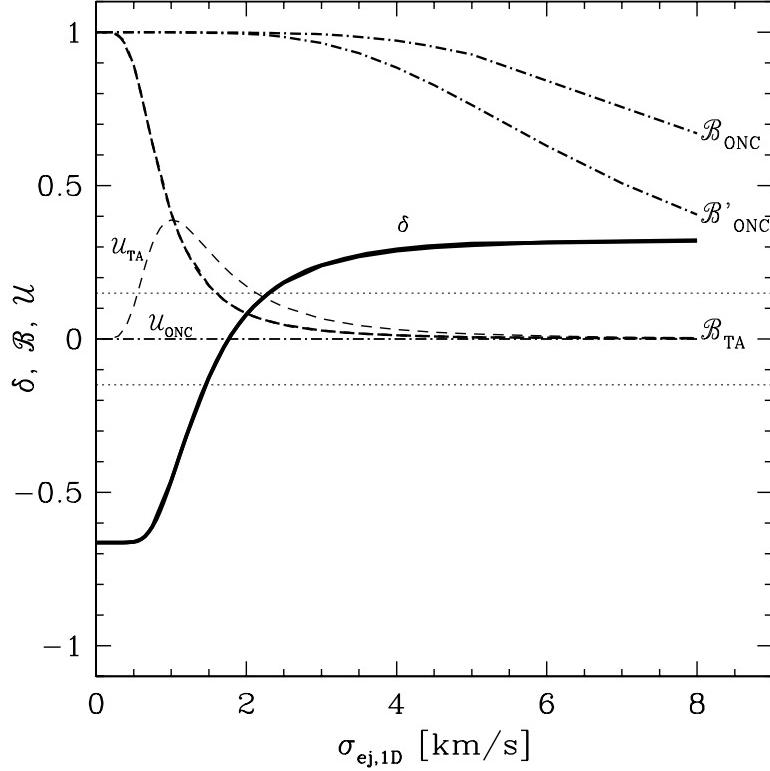


Figure 1. The dependence of the bound fraction of BDs, \mathcal{B} , and of the unbound but observable fraction, \mathcal{U} , on the one-dimensional dispersion of ejection velocities is shown for a typical TA group as the short-dashed curve, while for the embedded pre-ONC model it is shown as dot-dashed lines (\mathcal{B}_{ONC} is for $M_{\text{ecl+g}} = 9000 M_{\odot}$ while $\mathcal{B}'_{\text{ONC}}$ is for $M_{\text{ecl+g}} = 4500 M_{\odot}$). The difference δ (eq. 11) is plotted as the thick solid curve, while the thin dotted lines indicate the observational three-sigma range on δ . Note that δ does not depend sensitively on the mass of the ONC.

The calculated BD production rate (per star) can be used to estimate the sub-stellar IMF. Writing the IMF as a three-part power law (Kroupa 2002),

$$\xi(m) = k \begin{cases} \left(\frac{m}{0.08}\right)^{-\alpha_0} & , \quad m/M_{\odot} \leq 0.08, \\ \left(\frac{m}{0.08}\right)^{-1.3} & , \quad 0.08 < m/M_{\odot} \leq 0.5, \\ \left[\left(\frac{0.5}{0.08}\right)^{-1.3}\right] \left(\frac{m}{0.5}\right)^{-2.3} & , \quad 0.5 < m/M_{\odot}, \end{cases} \quad (13)$$

where k contains the desired scaling, it follows that

$$\mathcal{R} = \frac{\int_{0.02}^{0.08} \xi(m) dm}{\int_{0.15}^{1.0} \xi(m) dm}. \quad (14)$$

The integration limits in eq. 14 are given by the observational completeness limits of Briceno et al. (2002). Thus

$$\mathcal{R} = 0.21(0.29) \Rightarrow 0.0185(0.0255) = 0.08^{\alpha_0} \left(\frac{0.08^{1-\alpha_0} - 0.02^{1-\alpha_0}}{1 - \alpha_0} \right), \quad (15)$$

being the case for $\alpha_0 = -3.3$ ($\mathcal{R} = 0.21$) and $\alpha_0 = -2.1$ ($\mathcal{R} = 0.29$). This is much smaller than the estimate $\alpha_0 = +0.3 \pm 0.7$ for Galactic-field BDs implying $\mathcal{R} = 0.81$ (§ 6). Such a large observed value for α_0 would need larger ejection speeds of the embryos in order to reduce the observed number of BDs per star in TA. But by the above analysis we would find too many BDs per star in the ONC. We shall return to this in § 6.

In conclusion, this section introduced an analysis of the number of BDs per star observed in TA and ONC by assuming that the production mechanism of BDs is via embryo ejection and is the same in all environments. This assumption leads to agreement with the BD data in TA and the ONC and implies that the observed different number of BDs per star in the

TA groups and in the ONC can be explained (i) if the production rate of BDs per star in both environments is about one BD per four stars born, and (ii) if the intrinsic velocity dispersion of the BD population is the same in both environments, $\sigma_{ej,1D} \approx 2$ km/s. The prediction is that the TA groups ought to be surrounded by single BDs that have not yet been found because the deep surveys (Briceno et al. 2002) concentrate on the known stellar aggregates. The implied IMF for BDs falls off much too steeply when compared to the BD MF in the Galactic field, unless the empirical Galactic-field BD density has been overestimated (§ 6).

As stated at the end of § 1 three other mechanisms may add BDs. These are formation from very-low-mass cloud kernels with a star-like accretion history, through destruction of proto-stellar accretion envelopes due to photo-evaporation from a nearby massive star, or through hyperbolic collisions between accreting proto-stars in dense environments. In the next two sections we consider the latter two in turn, having already excluded the former as a major source of BDs. Photo-evaporation and collisions can only have been active in the ONC but not in the TA groups. It may therefore be possible that the observational finding $R_{obs,TA} < R_{obs,ONC}$ may be at least partially explained by having an additional source of BDs in the ONC. This would, however, imply that the production rate (per star) of BDs will be a function of the physical environment, contrary to the assumption posed above. The implications of this hypothesis on the global production rate of BDs will be addressed in § 6. Finally we note that whatever the formation mechanism for BDs is, the ONC cannot have produced more or less than $\mathcal{R}_{ONC} = 0.25 \pm 0.04$ BDs per star in total because $\mathcal{B}_{ONC} = 1$ for all reasonable $\sigma_{ej,1D}$.

3 THE PHOTO-EVAPORATION MODEL

The evaporation of circum-stellar disks through radiation from nearby O and B stars has been studied in much detail (Johnstone, Hollenbach & Bally 1998; Störzer & Hollenbach 1999; Scally & Clarke 2001) since the detection of such a process in the ONC with the HST (O'Dell, Wen & Hu 1993). Henney & O'Dell (1999) measure the mass-loss rates of four ONC stars with envelopes, and find that they could not have been exposed to the UV flux from the central O6 star (θ^1 Ori C) for longer than about 10^4 yr. These particular objects could be crossing the inner cluster region after spending more time at larger radii. However, the large proportion of stars with circum-stellar material does indicate that the destructive irradiation may indeed have turned on recently, probably through the very recent emergence or birth of the main ionising star θ^1 Ori C (Kroupa, Petr & McCaughrean 1999). Matsuyama, Johnstone & Hartmann (2003) also estimate a short photo-evaporation time-scale of the observed circum-stellar material through UV flux from external O stars in the central region of the ONC.

The reported short photo-evaporation rates of circum-stellar material thus suggests that very-low mass proto-stars may be severely affected if present close to an O star. One way to produce BDs and FFLOPs may be through removal of the accretion envelopes from low-mass hydrostatic cores that otherwise would become very-low-mass stars, by heating of the outer envelopes by the intense radiation from nearby O stars (Kroupa 2001; Whitworth & Zinnecker 2003; Preibisch, Stanke & Zinnecker 2003). This process for generating BDs and FFLOPs can only occur during the first 0.1 Myr of a proto-star's life while most of the mass of a proto-star is in an accretion envelope, and can only occur in rich clusters hosting O stars and cannot give rise to the BD population detected in TA. The large fraction of young BDs with infrared excesses indicative of disks in the central ONC (Muensch et al. 2001) would then constitute nearly naked embryos, the envelopes of which have not yet been completely removed.

To estimate the effect photo-evaporation of accretion envelopes may have on the MF we device a very simple model, rather than applying the elaborate radiation transfer treatment which requires the introduction of a number of parameters (mass profile and extend, mass flow geometry and rates, opacities) so as to make the problem tractable and which is dealt with in detail by Johnstone et al. (1998) and Störzer & Hollenbach (1999), among others. It will be seen that our estimates turn out to be reasonable.

The binding energy of the envelope is compared with the radiation energy received by a protostar which may have already formed a hydrostatic core. The initial binding energy of the protostar with mass $m_{ps,i}$ and radius R_{ps} is

$$E_{b,i} = -\frac{G m_{ps,i}^2}{R_{ps}}. \quad (16)$$

If the protostar receives an amount of external energy $E_{inp} \equiv \delta E_b$ this may lead to the loss of mass in the outermost envelope, $\delta m \equiv m_{ps,i} - m_{ps,f} \geq 0$. Writing

$$\begin{aligned} \delta E_b &= E_{b,i} - E_{b,f} \\ &= -\frac{G}{R_{ps}} (m_{ps,i}^2 - m_{ps,f}^2), \end{aligned} \quad (17)$$

leads to

$$\delta m = \left[1 - \left(1 - \frac{E_{inp}}{|E_{b,i}|} \right)^{\frac{1}{2}} \right] m_{ps,i}. \quad (18)$$

The incident energy received by the protostar over a time-span δt is

$$E_{\text{inp}} = \kappa \phi L_u \delta t, \quad (19)$$

where the primary ionising star has a luminosity L_u , κ is an efficiency used here to take into account that only a small fraction of emitted photons will be converted to heat energy in the proto-stellar envelope. If the protostar is situated a distance R from the O star only a fraction

$$\phi = \frac{\pi R_{\text{ps}}^2}{4\pi R^2} \quad (20)$$

of the emitted energy is received by the protostar. For example, an O5 star ($L_u = 10^{5.4}$ erg/s) inputs sufficient energy over $\delta t = 0.1$ Myr into the envelope of a protostar with $R_{\text{ps}} = 10$ AU and mass $m_{\text{ps}} = 0.3 M_\odot$ on a circular orbit around the O star with radius $R = 0.3$ pc to remove 0.6 per cent of the proto-star's mass, assuming $\kappa = 0.1$. This is essentially the same result as obtained from a much more sophisticated treatment of photo-evaporation: From eqn. 2 in Scally & Clarke (2001), which is applicable for an external radiation field dominated by far ultraviolet photons, a mass loss of 0.6 per cent is arrived at over 0.1 Myr.

The overall effect for an ensemble of 10^5 proto-stars on circular orbits with $R = 0.1$ pc is illustrated in Fig. 2 for two proto-stellar MFs that are truncated at the hydrogen-burning mass limit. Such a truncation is suggested by the reasoning of § 1 that BDs do not appear to have the same formation history as stars and therefore appear to originate through a mechanism that differs from that of most stars which presumably manage to accrete their available gas reservoir. The figure shows that if the proto-stellar MF is identical to the standard Galactic-field stellar IMF, then after 0.1 Myr the resulting stellar IMF may contain, within 0.1 pc of the main ionising star, far too few M dwarfs and BDs compared to observational constraints on the IMF in the central ONC for example (Muensch et al. 2001). If, however, the proto-stellar MF is a Salpeter MF ($\alpha = +2.3, m \geq 0.08 M_\odot$), then the observed stellar IMF may be obtained, but a deficit of BDs relative to the Galactic-field IMF may nevertheless be evident. Note that the results arrived at here may over-estimate photo-evaporation for $m_{\text{ps},i} \gtrsim 0.3 M_\odot$ relative to less-massive proto-stars because their shorter dynamical time and thus shorter collapse-phase has not been taken into account, in order not to introduce additional parameters into the model. Instead, it was assumed that proto-stars spend 0.1 Myr in an extended state independent of $m_{\text{ps},i}$.

A single pre-stellar power-law MF that would produce only stars can therefore be transformed to a MF with the correct shape and with BDs and FFLOPs. The above estimate is very crude, and the pre-stellar clump MF observed by Motte, André & Néri (1998) in ρ Oph which does not host an O star is not a single power-law form but already has the shape of the standard IMF, challenging the possibility that photo-evaporation may be an important BD production channel. The result obtained here by simply setting the few parameters to reasonable values, demonstrates above all else that photo-evaporation of accretion envelopes may be an important process acting to shape the IMF near and below the sub-stellar boundary within the immediate vicinity of ionising stars.

Photo-evaporation would also affect forming binary systems by the removal of binding mass from the proto-binary. The result (widened binary or complete disruption) depends on the amount and rate of mass loss (e.g. Hut & Verhulst 1981), and is not considered further here. It is only pointed out that this is a mechanism that would lead to systematic changes in binary properties with decreasing primary mass in the sense of producing wider and fewer binaries with decreasing primary mass. The results of Close et al. (2003), Gizis et al. (2003), Bouy et al. (2003) and Martín et al. (2003) for very-low-mass stars and for BDs in the Galactic field and the Pleiades do not support this, however, because their separation distribution appears to be very narrow and truncated near 20 AU, with a maximum near 4 AU, unless most of the field BDs do not stem from ONC-type clusters.

Photo-evaporation has an important kinematical implication that may be used to test it. Only those proto-stars will lose substantial mass from their accretion envelope that spend sufficient time near the dominating O star. Since most young clusters have their O stars located near their centres, this may transform into a kinematical bias: only those accreting proto-stars that have a low-enough velocity dispersion will stay long enough near the cluster centre to have a significant fraction of mass removed that would otherwise have ended up in the star.

A population of accreting proto-stars that spend a time δt confined within a radius R_{BD} has a velocity dispersion $\sigma_{\text{BD}} \approx R_{\text{BD}}/\delta t$. The bulk velocity dispersion of the cluster which is assumed to be in virial equilibrium before gas expulsion (Kroupa & Boily 2003) is $\sigma_{\text{cl}}^2 \approx G M_{\text{ecl+g}}/2 R_{0.5}$, so that

$$\frac{\sigma_{\text{BD}}}{\sigma_{\text{cl}}} = \frac{1}{\sqrt{\epsilon}} \frac{R_{\text{BD}}}{\delta t} \left(\frac{2 R_{0.5}}{G M_{\text{ecl}}} \right)^{1/2}. \quad (21)$$

The stellar mass of the cluster, $M_{\text{ecl}} = M_{\text{ecl+g}}/\epsilon$ for a star-formation efficiency, ϵ , of 33 per cent, can be related simply to the mass of the most massive star, m_u , by assuming the IMF is a Salpeter power-law and insisting that there is only one star with mass m_u : $M_{\text{ecl}} = \int_{0.1}^{m_u} m \xi(m) dm$, $\xi(m) = k m^{-2.3}$, $1 = \int_{m_u}^\infty \xi(m) dm$. With a mass-luminosity relation for massive stars of the form $L_u/L_\odot = 1.2 (m_u/M_\odot)^{3.8}$ (Cox 2000, p. 382) the following expression results,

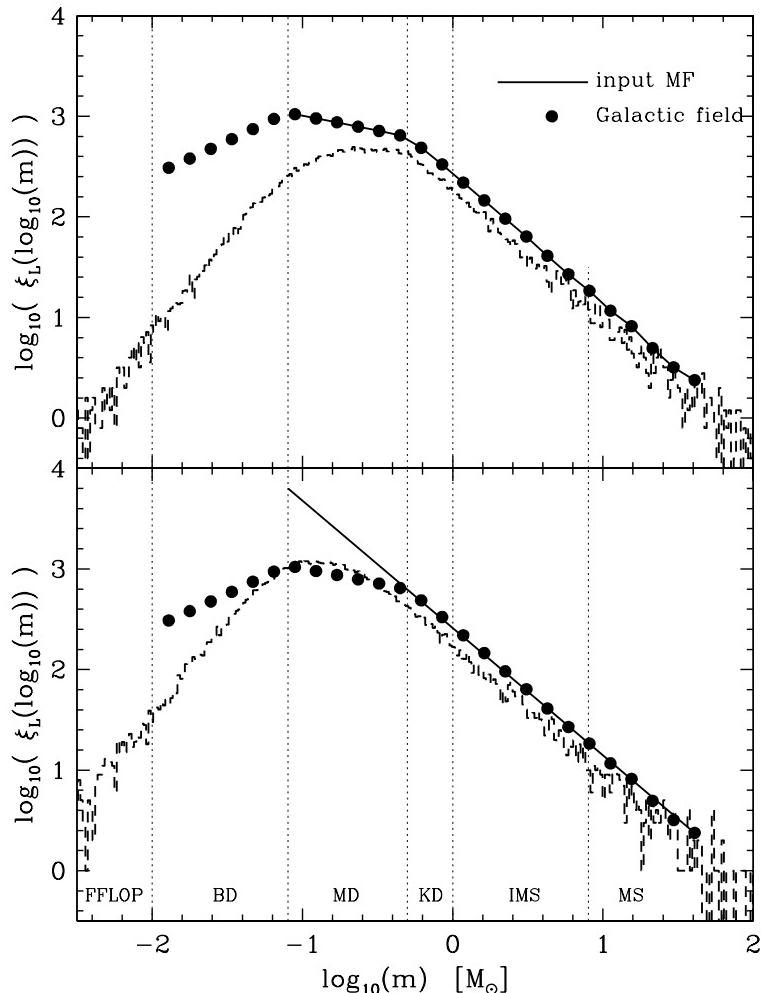


Figure 2. The IMF resulting from the photo-evaporation envelope-destruction model. In the upper panel the input proto-stellar MF is the standard IMF with $m \geq 0.08 M_\odot$, while in the lower panel a Salpeter proto-stellar MF for $m \geq 0.08 M_\odot$ is adopted. In both panels the dots are the standard or average Galactic-field IMF for $m \geq 0.01 M_\odot$. The model assumes $\delta t = 0.1$ Myr, $\kappa = 0.1$, $R = 0.1$ pc, $L_u = 10^{5.4} L_\odot$ (an O5 star). The vertical dotted lines delineate simplified object types (MD,KD = M,K dwarf, IMS = intermediate mass star, MS = massive star).

$$\frac{M_{\text{ecl}}}{M_\odot} = 8.24 \left(\frac{L_u}{L_\odot} \right)^{0.355} - 2.73 \left(\frac{L_u}{L_\odot} \right)^{0.263}. \quad (22)$$

To illustrate the kind of kinematical effect one may expect it is useful to take R_{BD} to be that radius within which all $m_{\text{ps}} = 0.3 M_\odot$ proto-stars are converted to $0.08 M_\odot$ proto-stars within a time $\delta t = 0.1$ Myr. From eq. 18 follows, with the condition $\delta m \leq m_{\text{ps}}$,

$$R = \left(\frac{\kappa L_u \delta t R_{\text{ps}}^3}{4 G m_{\text{ps}}^2} \right)^{1/2} \left(2 \left(\frac{\delta m}{m_{\text{ps}}} \right) - \left(\frac{\delta m}{m_{\text{ps}}} \right)^2 \right)^{-1/2}. \quad (23)$$

With $m_{\text{ps}} = 0.3 M_\odot$ and $\delta m = 0.22 M_\odot$ an estimate for $R_{\text{BD}} = R$ results.

Fig. 3 illustrates the effect for a cluster with half-mass radius $R_{0.5} = 0.4$ pc and for different central photo-ionising stars. The figure shows that the BD and FFLOP population should be kinematically colder than the stars ($\sigma_{\text{BD}} < \sigma_{\text{cl}}$), and that the effect may be more pronounced for less massive clusters. However, this only applies if most massive stars form near the centre of their cluster. Should the massive stars form within sub-clusters throughout the volume of the emerging cluster and then sink to the centre through dynamical mass segregation then the associated photo-evaporated BDs will mix with

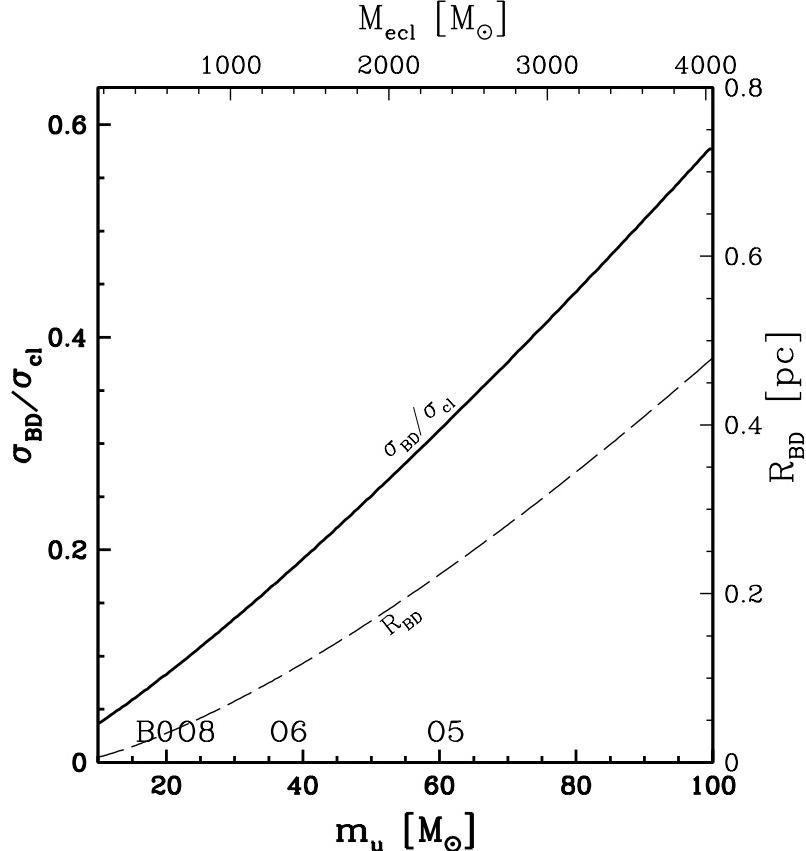


Figure 3. The ratio of the velocity dispersion of the emerging BD and FFLOP population to the stellar velocity dispersion in the cluster as a function of the mass, m_u , of the central ionising star (solid line). The corresponding stellar mass of the cluster, M_{ecl} , is given on the top axis assuming the IMF is a Salpeter power-law. The radius, R_{BD} , within which a proto-star initially with a mass of $0.3 M_{\odot}$ is reduced to one with a mass of $0.08 M_{\odot}$ is shown as the dashed curve with corresponding axis on the right. The model assumes $\delta t = 0.1$ Myr, $\kappa = 0.1$, $R_{0.5} = 0.4$ pc, $m_{\text{ps}} = 0.3 M_{\odot}$, $\delta m = 0.22 M_{\odot}$. For example, a central O5 star will transform all $< 0.3 M_{\odot}$ proto-stars to sub-stellar objects if they remain within a radius of $R_{\text{BD}} \approx 0.2$ pc for 0.1 Myr. This population of BDs and FFLOPs has a velocity dispersion $\sigma_{\text{BD}} \approx 0.3 \sigma_{\text{cl}}$. The data plotted here are to be understood as illustrative of the type of effect that we may expect (kinematically ‘cold’ populations of BDs centred about ‘their’ massive stars in rich young clusters).

the cluster population and acquire more or less virial velocities by the time the sub-structure has been erased through the merging process.

Given the numbers presented in Fig. 3 it is possible to estimate which fraction of the stellar population could be photo-evaporated BDs. In the ONC that has one O6 star, $R_{\text{BD}} \approx 0.1$ pc, which is much smaller than the half-mass radius of the pre-gas-expulsion cluster, $R_{0.5, \text{ONC}} \approx 0.4$ pc, the fraction of the stellar population that are photo-evaporated BDs is $\mathcal{R}_{\text{env}} = 0.007$, assuming the cluster had a Plummer density profile (KAH) and if all M stars within R_{BD} were to transform to BDs (M dwarfs contribute roughly 50 per cent to a stellar population, Kroupa 2002). This estimate of \mathcal{R}_{env} is valid for the embedded cluster. Once the gas is removed and the cluster expands the kinematically colder photo-evaporated BD population will expand less than the kinematically hotter stellar plus ejected-BD component, so that an observer will today find a larger number of photo-evaporated BDs per star in the central region of the ONC. An improved estimate of the contribution by photo-evaporated BDs awaits N -body computations as energy equipartition between the BDs and stars is likely to affect the results.

The above estimate for R_{env} assumes that the ONC had only one O6 star ($^1\text{Ori C}$). Photo-evaporation could have been more effective should the initial cluster core have contained a larger number of massive stars. This is possible because the presently observed Trapezium configuration at the cluster centre is dynamically highly unstable. Most of the Trapezium stars are higher-order multiple systems (Preibisch et al 1999) that are interacting with each other on a time-scale given by the dynamical time of the core of massive stars. Thus, assuming the core had a dimension $R_{\text{core}} = 0.05$ pc $\approx 10^4$ AU and a mass $M_{\text{core}} \approx 150 M_{\odot}$ it should decay on a time-scale of approximately 4×10^4 yr (eq. 1). Explosive gas expulsion together

with a low star formation efficiency in the core would also expand it and allow massive stars to leave the central region (Vine & Bonnell 2003). The very existence of the Trapezium at the present time therefore poses an important challenge for understanding the ONC. One possible solution is that the proto-ONC may have had a more populated cluster core of which we today only see one snap-shot before it decays further. Also, the Trapezium may actually be rather young, as evidenced by the short photo-evaporation time-scale of stellar envelopes and the apparent youth of the dynamical configuration of the ONC (Kroupa et al. 1999).

The photo-evaporation model predicts the stellar IMF to vary with conditions, since it implies that in dense and populous clusters some or many of the M dwarfs ought to be failed G dwarfs. Briceno et al. (2002) and KBDM show that the stellar IMF in TA and the ONC are very similar in the mass range $0.1 - 1 M_{\odot}$, which ought not to be the case if photo-evaporation of envelopes does play a major role. Agreement of different IMFs in the stellar regime does not necessarily preclude photo-evaporation being an important mechanism, because, in essence (eq. 18) $\delta m/m_{\text{ps},i} \propto m_{\text{ps},i}^{-1}$ and because more massive proto-stars collapse to compact morphologies more rapidly than less-massive proto-stars (this has not been modelled here) so that the least-massive proto-stars are affected significantly more than typical proto-stars. The emerging IMF will therefore be most sensitive to the presence of O stars in the sub-stellar mass regime.

For very massive clusters (stellar super-clusters), which may contain many stars with masses reaching to $150 M_{\odot}$, the radius for producing photo-evaporated BDs from low-mass proto-stars may be similar to the radius of the whole cluster, $R_{\text{BD}} \approx R_{\text{cl}}$. *Globular clusters may thus have a significant population of photo-evaporated BDs.* The globular cluster stellar MFs appear to be rather similar to the stellar MFs in young Galactic clusters (see Kroupa 2002 for a review), although there is some tentative evidence that young Galactic clusters may have an IMF decreasing more steeply with increasing stellar mass (Kroupa 2001), thus allowing some constraints on the degree with which photo-evaporation may affect the stellar IMF in clusters that still contain or in the past contained O stars.

4 THE COLLISION MODEL

In dense clusters accreting proto-stars can pass each other on hyperbolic orbits such that they loose a part of their accretion envelope during the collision, the embryos being removed from their gas reservoir (Price & Podsiadlowski 1995). The mechanism for accretion-envelope removal envisioned here is different to the embryo-ejection model because previously unbound proto-stars collide with hyperbolic velocities whereby the envelopes interact hydrodynamically thus dissipating the relative kinetic energy, while the compact hydrostatic cores continue their fly-by largely unhindered. The so produced BDs or FFLOPs remain trapped in the cluster potential. *The primary difference to the embryo-ejection model is that the velocity dispersion of the BDs is the same as that of the stars, while embryo ejection leads to a larger BD velocity dispersion in the cluster.* Any such destructive encounter will disrupt the proto-binary within which the proto-star was accreting. Thus, in the ONC some of the accreting BD companions may have been lost from their parent systems and, having been deprived from gas to accrete, they may have remained sub-stellar.

In TA stellar-dynamical encounters are rare (Kroupa & Bouvier 2003), and the accreting hydrostatic cores remain companions locked to the stars. They can continue to accrete for 1 Myr (or longer) since they do not experience close encounters. It would require a mass accretion rate on the BD companion of only about $\dot{m} = 10^{-7} M_{\odot}/\text{yr}$ during the first Myr for it to become a star. This is much larger than the currently estimated \dot{m} for young BDs ($\approx 10^{-9} M_{\odot}/\text{yr}$) but, like for stars, it is likely that the mass accretion rate rapidly decreases with time. It is typically $10^{-8} M_{\odot}/\text{yr}$ for a 2 Myr T Tauri star, but is believed to be as high as $10^{-6} M_{\odot}/\text{yr}$ during the embedded proto-stellar phase which lasts several 10^5 yr. Initial BD companions to stars in TA could therefore become (low-mass) stars in about 1 Myr (fig. 1 in Reipurth & Clarke 2001). This could account both for the deficiency of isolated BDs in TA compared to the ONC and for the period distribution of stellar binaries in TA, since most/all potential BD companions would have evolved into stellar companions. This is probably the physical reason why the star-like BD flavour had to be excluded in § 1 as contributing a significant fraction of the overall BD population.

Assuming the same IMF in TA and the ONC which is truncated at the hydrogen burning mass limit (as in § 3) we want to investigate if the collision process may be relevant for the observed different number of BDs per star (and FFLOPs) in the ONC and TA.

The role of collision-induced accretion-envelope removal has been studied in detail by Price & Podsiadlowski (1995) for a range of environments. The general result of their work is that the stellar (and sub-stellar) IMF should vary in dependence of the richness of the cluster. Their models can be applied to the case of the ONC to obtain an indication of the type of effect that might occur. We note however, that a number of parameters that describe the model IMF obtained in this way are rather uncertain, such as the star-formation history, the shape of the proto-stellar envelopes and mass-accretion rates.

The proto-stellar collision rate (per cluster member) is given by their eq. 2.1,

$$\beta_{\text{pp}} = \frac{3 R_{\text{ps}}^2 \sigma_{\text{cl}}}{4 R_{\text{cl}}^3}, \quad (24)$$

where R_{cl} is the characteristic cluster radius. For the proto-ONC $R_{\text{cl}} \approx 0.5$ pc and $\sigma_{\text{cl}} \approx 5$ pc/Myr (KAH) so that $\beta_{\text{pp}} \approx R_{\text{ps}}[\text{pc}]^2 \times 3 \times 10^{-5}$ yr $^{-1}$ per member. For $R_{\text{ps}} \leq 100$ AU = $10^{-3.31}$ pc, $\beta_{\text{pp}} \leq 10^{-11}$ yr $^{-1}$ per member. Such a small β_{pp} implies a Salpeter IMF down to about $0.01 M_{\odot}$ (fig. 3b in Price & Podsiadlowski 1995), which is not observed. Also, over 0.1 Myr there are $\leq 10^{-6}$ collisions per member with impact parameters ≤ 200 AU. With 10^4 ONC members (KAH) we obtain $\leq 10^{-2}$ possible BDs in the ONC. This is much smaller than the few hundred BDs found so far, indicating that collisional processes are completely negligible in the ONC, as already stressed in Kroupa (2002).

Scally & Clarke (2001) perform N -body computations of an ONC-type cluster to estimate the number of encounters that could have truncated circum-stellar disks. Their model cluster consists of 4000 stars with a half-mass radius of 1 pc, and they find that by 2.89 Myr only about 4 per cent of the stars suffered encounters with peri-astra less than 100 AU. The encounter rate is approximately $\rho \pi R_{\text{ps}}^2 \sigma_{\text{cl}}$, where ρ is the cluster number density. Scaling this to our ONC model, the 4 per cent thus needs to be multiplied by $(\rho/\rho_{\text{SC}}) \times (R_{\text{ps}}/100 \text{ AU})^2 \times (\sigma_{\text{cl}}/\sigma_{\text{cl,SC}})$, where the values with sub-script SC refer to the Scally & Clarke ONC model. We have $\rho/\rho_{\text{SC}} = (10000/0.5^3)/4000 = 20$, $\sigma_{\text{cl}}/\sigma_{\text{cl,SC}} = 7/4.3 = 1.6$. The ONC model used here thus implies that about 1 per cent of all stars will have experienced encounters with peri-astra less than 10 AU over 2.89 Myr, or 0.04 per cent over a time span of 0.1 Myr, which is the life-time of a proto-star before it evolves to a more compact star plus low-mass disk morphology. For an ONC membership of 10^4 this amounts to 4 possible collisional BDs confirming that collisional processes will have been negligible in the ONC.

Overall therefore, *the evidence points strongly against collisional effects being an important channel for producing BDs.*

5 A COMBINED MODEL

In § 2 a successful model was developed that accounts for the observed number of BDs per star in the TA and the ONC by assuming that BDs come in only one flavour, namely the embryo-ejected type. However, § 3 demonstrated that photo-evaporated BDs may also constitute an existing BD flavour in clusters containing O stars, while star-like (§ 1) and collisional (§ 4) BDs appear to be very rare.

The stars in the ONC are faster rotators than in TA (Clarke & Bouvier 2000), and this may be another indicator that some stars may have lost their accretion envelopes earlier in the ONC thus reducing disk breaking. The prediction of the photo-evaporation (and collision) scenario is that *the binary proportion should decrease with the rotational velocity of the stars*. That is, if the ONC late-type stars are split into fast and slow rotators, then the fast rotators should have a smaller binary fraction than the slow rotators because they may have suffered mass-loss through photo-evaporation or an encounter.

In this section we consider all four BD flavours to investigate if a consistent description of the observations can be attained (the star-like and collisional BDs are kept only formally). Here the ansatz is to again assume that the ejected embryos have the same distribution function of ejection velocities in TA and the ONC (eqs 2 and 3): that in TA and the ONC the ejections occur from dynamically unstable small- N systems that have the same characteristics in both star-forming regions. As in § 2 ejected BDs can be lost from the cluster (ONC) or stellar group (TA), while photo-evaporated (and star-like and collisional) embryos are retained in the cluster or group.

For a BD and FFLOP population that consists of ejected, photo-evaporated and collisional embryos an observer will detect (cf. eq. 8)

$$\mathcal{R}_{\text{obs}} = (1 + f) [\mathcal{R}_{\text{ej}} (\mathcal{B} + \mathcal{U}) + \mathcal{R}_{\text{o}}] \quad (25)$$

BDs per stellar system, where $\mathcal{R}_{\text{o}} = \mathcal{R}_{\text{env}} + \mathcal{R}_{\text{st}}$ and $\mathcal{R}_{\text{env}} = \mathcal{R}_{\text{phot}} + \mathcal{R}_{\text{coll}}$. Here $\mathcal{R}_{\text{st}} \equiv N_{\text{BD,st}}/N_{\text{st,tot}}$ is the number of star-like BDs per star, $\mathcal{R}_{\text{phot}} \equiv N_{\text{BD,phot}}/N_{\text{st,tot}}$ is the number of photo-evaporated BDs per star, $\mathcal{R}_{\text{coll}} \equiv N_{\text{BD,coll}}/N_{\text{st,tot}}$ is the number of collisional BDs per star, and $\mathcal{R}_{\text{ej}} \equiv N_{\text{BD,ej}}/N_{\text{st,tot}}$ is the number of BDs per star produced by embryo ejection, while $\mathcal{B}(\sigma_{\text{ej,1D}}, M_{\text{ej+g}})$ is the fraction of ejected BDs retained in the cluster or group potential, and $\mathcal{U}(\sigma_{\text{ej,1D}}, M_{\text{ej+g}})$ is the fraction of ejected and unbound BDs which are still detected within the observational survey region because they haven't drifted far enough by the time of observation. Finally, the evidence points to $\mathcal{R}_{\text{st}} \approx 0$ (§ 1) and $\mathcal{R}_{\text{coll}} \approx 0$ (§ 4).

To assess what minimum R_{ej} can give rise to the observed values in TA ($\mathcal{R}_{\text{obs,TA}} = 0.17 \pm 0.06$) and the ONC ($\mathcal{R}_{\text{obs,ONC}} = 0.38 \pm 0.06$) for the same distribution of ejection velocities, eq. 25 is solved for \mathcal{R}_{ej} to obtain ($\mathcal{R}_{\text{env,TA}} = 0$)

$$\begin{aligned} \mathcal{R}_{\text{ej,TA}} &= \frac{\mathcal{R}_{\text{obs,TA}}}{1 + f_{\text{TA}}} (\mathcal{B}_{\text{TA}} + \mathcal{U}_{\text{TA}})^{-1}, \quad \text{and} \\ \mathcal{R}_{\text{ej,ONC}} &= \left(\frac{\mathcal{R}_{\text{obs,ONC}}}{1 + f_{\text{ONC}}} - \mathcal{R}_{\text{env}} \right) (\mathcal{B}_{\text{ONC}} + \mathcal{U}_{\text{ONC}})^{-1}. \end{aligned} \quad (26)$$

Note that $\mathcal{U}_{\text{ONC}} = 0$ for $\sigma_{\text{ej,1D}} < 8$ km/s (Fig. 1). The result is displayed in Fig. 4 for $\mathcal{R}_{\text{env}} = 0$ and $\mathcal{R}_{\text{env}} = 0.23$. The result from § 2 is arrived at again: $\mathcal{R}_{\text{TA}} = \mathcal{R}_{\text{ONC}} = 0.21 - 0.29$ for $\sigma_{\text{ej,1D}} \approx 2$ km/s. However, if about 0.23 BDs per star are produced through photo-evaporative envelope loss in the ONC, then $\mathcal{R}_{\text{TA}} = \mathcal{R}_{\text{ONC}} \approx 0.06$ for $\sigma_{\text{ej,1D}} \lesssim 0.8$ km/s. In this case a large fraction of ejected BDs are retained in both, the TA groups and in the ONC ($\mathcal{B}_{\text{TA}} \gtrsim 0.5$; $\mathcal{B}_{\text{ONC}} \approx 1$, Fig. 1).

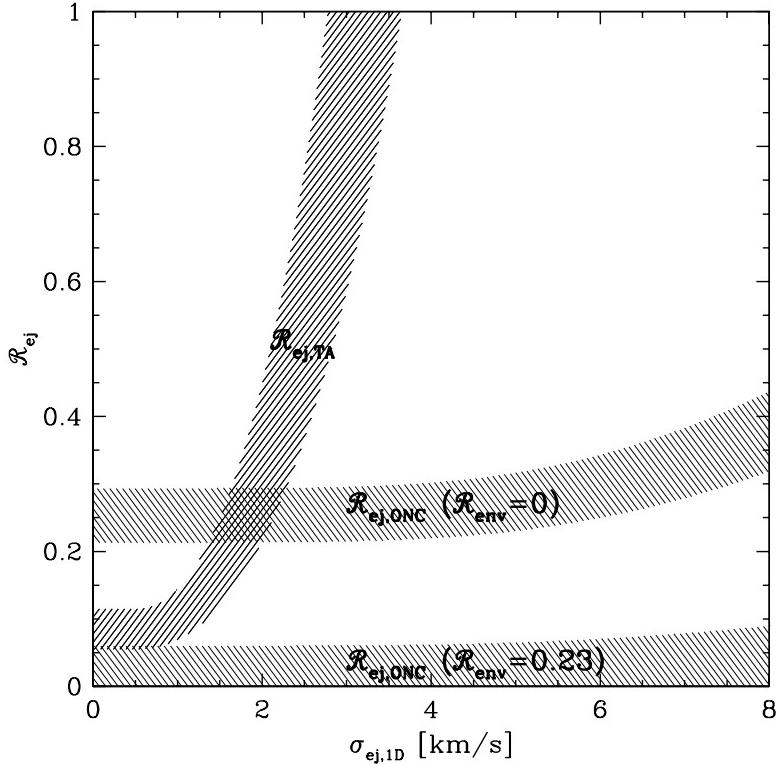


Figure 4. The number of ejected BDs per star (\mathcal{R}_{ej}) in TA and the ONC as a function of the velocity dispersion of the ejected population. If accretion envelope removal through photo-evaporation or stellar-dynamical collisions plays no role in creating BDs and FFLOPs from embryos that would otherwise become stars ($\mathcal{R}_{\text{env}} = 0$) then about one BD per four stars is produced through ejection of unfinished embryos with $\sigma_{\text{ej},1\text{D}} \approx 2$ km/s in TA and the ONC (recovering the result from § 2). If, on the other hand, $\mathcal{R}_{\text{env}} = 0.23$ photo-evaporated BDs per star in the ONC, then the observational data require the rate of embryo ejection to be reduced to 6 BDs per 100 stars ($\mathcal{R}_{\text{ej}} \approx 0.06$), and $\sigma_{\text{ej},1\text{D}} < 0.8$ km/s in TA and the ONC. Note that in all cases $\delta = 0$ (eq. 11).

It therefore seems possible that BDs come mostly in two flavours, namely as ejected embryos from all star forming regions and as photo-evaporated embryos. Present data for TA and the ONC allow limits to be placed on the production rate (per star) of each flavour, ranging from 0.21–0.29 ejected BDs per star if the other three production channels can be neglected altogether, down to 0.06 ejected BDs per star if photo-evaporated BDs contribute 0.23 BDs per star in clusters similar to the ONC.

6 DOES BROWN-DWARF BIRTH DEPEND ON ENVIRONMENTAL CONDITIONS?

As pointed out in § 2 there appears to exist a disconcerting discrepancy between the observed number of BDs per star in TA and the ONC and the observed number of BDs in the Galactic field. The analysis performed above suggests that *there can be at most $\mathcal{R}_{\text{ej}} \approx 0.25 \pm 0.04$ BDs per star produced as ejected embryos with a velocity dispersion of about 2 km/s if photo-evaporated BDs can be neglected*. If, on the other hand, $\mathcal{R}_{\text{env}} = 0.23$ BDs per star are embryos that lost their accretion envelope due to photo-evaporation in ONC-type clusters, then only $\mathcal{R}_{\text{ej}} \approx 0.06$ BDs per star are created as ejected embryos in all environments with a small velocity dispersion of only about 0.8 km/s or less.

In young clusters similar to the ONC the maximum number of BDs per star is thus $\mathcal{R} = 0.25 + 0.12 = 0.37$ (three-sigma limit). This is significantly smaller than the number of BDs per star expected from the Galactic-field MF (eq. 14, $\mathcal{R} = 0.81$ for $\alpha_0 = +0.3$, Kroupa 2002; $\mathcal{R} \approx 1$, Chabrier 2002), unless the surveys lead to an overestimate of the number of BDs per star in the Galactic field.

This problem may be remedied by dropping the ansatz made in the above analysis that the ejected-embryo population have the same distribution of ejection velocities, independent of the star-formation conditions, and that the number of ejected

BDs per star produced be the same. That is, we now allow the physical properties of the fragmenting cloud kernels to vary with the conditions in their molecular cloud.

Thus, from Fig. 4, $\mathcal{R}_{\text{ej,TA}} = 1$ is consistent with the observational datum for TA if $\sigma_{\text{ej,1D}} \approx 3$ km/s. The weak potentials of the TA groups cannot hold most of the ejected BDs, and *the prediction would be that a large fraction of the ejected BDs are distributed throughout the star-forming area but outside the surveyed groups, $\mathcal{B}_{\text{TA}} \approx 0.05$ in Fig. 1, and a BD with a velocity of 3 km/s leaves the Briceno et al. (2002) survey area, 2.3 pc x 2.3 pc, within less than 1 Myr.* On the other hand, the ONC has never produced the number of BDs per star evident in the Galactic field, unless the dispersion of velocities was unreasonably high (Fig. 4: $\sigma_{\text{ej,1D}} > 10$ km/s for $\mathcal{R}_{\text{ej,ONC}} \approx 1$). The potential well of the ONC is so deep that virtually all BDs are kept for reasonable ejection velocity-dispersions, and the observational datum, $\mathcal{R}_{\text{obs,ONC}}$, forces the number of ejected BDs per star to lie near 0.25 ± 0.04 for $\sigma_{\text{ej,1D}} \lesssim 5$ km/s ($\mathcal{B}_{\text{ONC}} > 0.9$, Fig. 1). *Adding other BDs flavours reduces the possible contribution by ejected BDs even further, and it appears thus that most Galactic-field BDs may not have been born in ONC-type clusters, unless the number of Galactic-field BDs is overestimated.*

This interpretation of the data would imply that cloud kernels in TA can fragment more vigorously thereby ejecting many more unfinished embryos than in the early ONC. However, this would appear to contradict the Jeans-mass argument (§ 1). An unbiased determination of \mathcal{R} in the solar-neighbourhood is not a trivial matter given the various uncertainties (unknown ages, masses and distances) that still affect the census of field BDs so that the solutions presented in § 2 and § 5 that rely on a universal ejection process are probably to be favoured.

7 CONCLUDING REMARKS

Recent findings on BD properties are now allowing interesting insights into the nature and origin of BDs. The observational surveys by Close et al. (2003), Gizis et al. (2003), Bouy et al. (2003) and Martín et al. (2003), and the study by KBDM suggest that BDs probably did not form with the same properties as stars (i.e. as hydrostatic cores that accrete most of their available envelope mass), because the predicted properties of star-BD and BD-BD binaries are not consistent with available constraints. The star-BD and BD-BD binaries should have properties that are a natural extension of the trends seen among stars with decreasing primary mass, which does not appear to be the case as emphasised by Close et al. Most BDs therefore do not appear to have a star-like accretion history. Instead, the majority of BDs probably start-off like stars but their accretion is truncated through an external agent. The aim of this study is to investigate which implications the three possible truncation mechanisms (embryo ejection, photo-evaporation and hyperbolic collisions) may have on the observable properties and distribution of BDs.

The study performed here shows that the embryo-ejection hypothesis can lead to a consistent description of the number of BDs per star seen by Briceno et al. (2002) in the TA groups and in the central region of the ONC. Owing to the weaker gravitational field, TA groups retain a small fraction of their BDs, while the ONC captures most of them. *In both environments about one BD is ejected from a multiple system containing on average four stars ($\mathcal{R}_{\text{ej}} \approx 0.21 - 0.29$).* According to this picture the fragmenting cloud kernels would have, statistically, the same physical properties in TA and the ONC on scales less than a few hundred AU. The different stellar binary fraction in TA and in the ONC is taken into account explicitly in the calculation of R_{ej} . The dispersion of ejection velocities comes out to be about 2 km/s, and this poses the presently simplest and therefore favoured interpretation of the data. The rejection of the embryo-ejection hypothesis by other workers (§ 1) may not be valid because ejected BDs can retain disks (§ 2) and because the detected BDs have $v < v_{\text{in}}$, as otherwise they would not appear in the observed volumes, implying similar kinematics to the stars. Larger survey areas are needed to better address this latter point. An interesting possibility related to the embryo-ejection hypothesis is that the sharp rise of the MF observed by Muench et al. (2002, 2003) in the ONC and the IC 348 below $0.03 M_{\odot}$ may be due to the rapid dynamical decay of young many-planet systems.

In rich clusters that contain O stars photo-evaporation of the accretion envelope of low-mass hydrostatic cores, that would otherwise become M dwarfs, can instead produce a BD or a FFLOP. With this mechanism, a featureless Salpeter power-law proto-stellar MF, that would produce only stars in the absence of O stars, can transform to the observed Galactic-field IMF which has a flattening near $0.5 M_{\odot}$ and which contains BDs and FFLOPs. *A population of photo-evaporated BDs should have a smaller velocity dispersion than the stars, with a trend to smaller relative velocity dispersion for less massive clusters.* Photo-evaporated BDs should be confined to a small vicinity about the ionising star. Both of these observable diagnostics apply unless massive stars form with their own sub-clusters throughout the volume encompassing the emerging cluster, because the BD sub-populations will mix and virialise within the emerging cluster. In very massive stellar super clusters that contain many stars as massive as $150 M_{\odot}$ photo-evaporated BDs probably contribute significantly to the BD population. That the removal of accretion envelopes may have been occurring in the ONC is supported tentatively by the late-type stars in the ONC being faster rotators than in TA.

BDs and FFLOPs can also be produced through removal of accretion envelopes due to hyperbolic collisions of $\lesssim 0.1$ Myr

old proto-stars. The collision scenario predicts the binary fraction to decrease with increasing rotational velocity (§ 5). However, the expected rate of collisions is negligible in the ONC.

If the ansatz is retained that the physical properties of the fragmenting cloud kernels and thus the number of ejected BDs per star be the same independent of environment, then adding photo-evaporated BDs into the ONC reduces the allowed number of BDs that could have been produced in the TA groups and in the ONC as ejected embryos, from about one BD per four stars (in the absence of the other BD flavours) down to about six ejected BDs per 100 stars ($\mathcal{R}_{ej} \approx 0.06$) with a small dispersion of ejection velocities of $\sigma_{ej,1D} \lesssim 0.8$ km/s if there are 0.23 photo-evaporated BDs per star in the central region of the ONC.

The ansatz that R_{ej} and $\sigma_{ej,1D}$ be the same in TA and in the ONC leads to the uncomfortable situation that the number of BDs per star (maximally $\mathcal{R} = 0.37$, three-sigma value) is inconsistent with independent measurements of the BD MF in the Galactic field ($\mathcal{R} \approx 0.9$). Discarding this ansatz, it is found that only in TA can star formation have produced about one BD per star ($\mathcal{R}_{ej,TA} \approx 1$) if $\sigma_{ej,1D} \approx 3$ km/s. The observational data from the ONC do not allow one BD to have been produced per star in the proto-ONC. Instead, star formation in the ONC could only have produced at most 0.37 BDs per star either wholly as ejected embryos, or together with photo-evaporated BDs. *If the inferred number of BDs per star in the Galactic-field is not an overestimate, then this indicates that the number of BDs per star may depend sensitively on the star-forming conditions in the sense that low-mass tranquil star-formation may be producing most of the known BDs, while ONC-type clusters may be relatively inefficient in producing BDs.* Note that this conclusion would be opposite to an unreflected interpretation of the TA and ONC data (first sentence in the abstract) and would also be inconsistent with the Jeans-mass argument (§ 1).

The ONC datum used in the analysis presented here is based on the number of BDs per star in the central cluster region. Preibisch et al. (2003) find that this datum is consistent with the independent surveys by Muench et al. (2002) for the central region, and for the whole-ONC survey by Hillenbrand & Carpenter (2000). Preibisch et al. (2003) and Luhman et al. (2003) measure the BD content of IC 348 and find this cluster, which does not contain O stars and is intermediate in density between the TA groups and the ONC, to be similarly deficient in BDs (per star) as the TA groups. According to Preibisch et al. this may be due to most of the BDs in the ONC being of the photo-evaporated flavour, but they admit that this may be problematical since in the ONC significant photo-evaporation is limited to a relatively small radius around θ^1 Ori C. As suggested here, the ONC may have contained a larger number of massive stars that were expelled from a dynamically unstable cluster core, so that exclusion of photo-evaporation as the mechanism of providing a substantial number of BDs in the ONC may be premature. Preibisch et al. also point out that the embryo-ejection hypothesis may well be the main origin of most BDs, the ONC being much more efficient in capturing the BDs than the much less massive IC 348 cluster and the TA groups.

This work has found that embryo ejection is probably the main channel for producing BDs, but the photo-evaporated flavour probably also exists in rich clusters. The BD situation remains exciting and partially controversial; additional observational data are badly needed to help refine our understanding of the origin and nature of BDs and FFLOPs. Such data would be a census of BDs outside the stellar groups in TA, improved constraints on the binary properties of BD primaries, verification of the reported dramatic rise of the BD (or FFLOP) MF below $0.03 M_\odot$, as well as measurements of the velocity dispersion and rotational velocities of BDs and stars in clusters.

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